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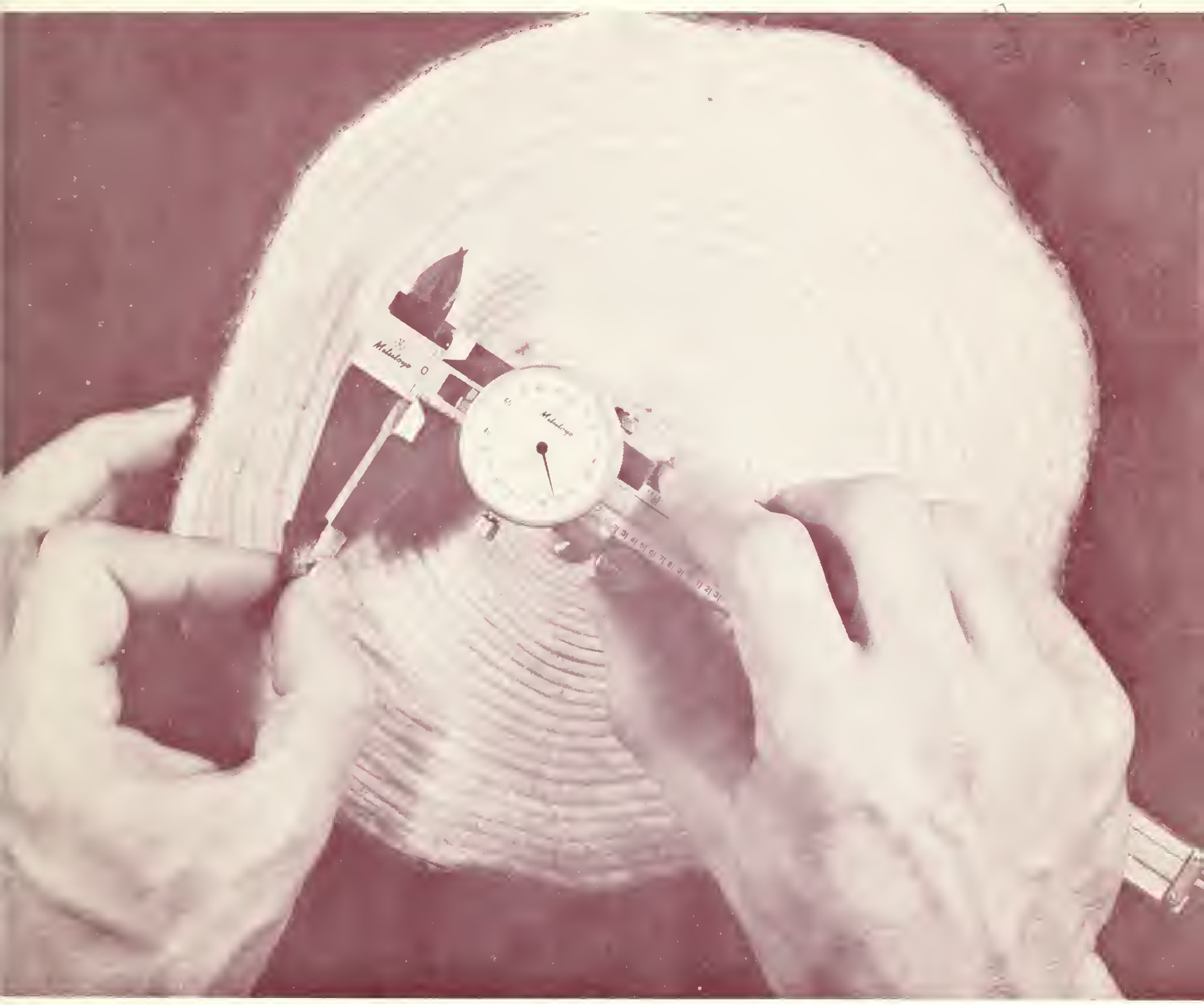
# Estimation of Phloem Thickness in Lodgepole Pine

## Dennis M. Cole



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EXPERIMENT STATION
Ogden, Utah 84401

# THE AUTHOR

DENNIS M. COLE is an Associate Research Silviculturist working on research in the silviculture of lodgepole pine, stationed at Bozeman, Montana. His studies have been primarily concerned with the description and management of growth and yield relationships of lodgepole pine forests.

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**Dennis M. Cole**

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Ogden, Utah 84401
Robert W. Harris, Director

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# ABSTRACT

Analysis of data from 288 trees shows that phloem thickness of lodgepole pines is strongly related to tree growth expressions that reflect past tree vigor, such as periodic basal area increment, and d.b.h. and tree height in conjunction with tree age. Broad habitat-type groupings also significantly influence phloem thickness. Equations presented for estimating phloem thickness of individual trees are usable in construction of phloem thickness distributions for lodgepole pine stands. Such distributions can aid in developing risk classifications for assessing vulnerability of lodgepole pine stands to mountain pine beetle attack.

# INTRODUCTION

In tree growth investigation, phloem thickness has been little studied until recently. Researchers and resource managers concerned with forests of lodgepole pine (*Pinus contorta* Dougl.) are interested in its relation to the activity of the mountain pine beetle (*Dendroctonus ponderosae* Hopk.).

The mountain pine beetle shows a strong preference for large-diameter trees in lodgepole pine stands (Hopping and Beall 1948, Cole and Amman 1969). Recent evidence indicates that brood survival of the beetles is related to thickness of phloem, the beetles being generally unable to produce a successful brood in trees with phloem thickness of less than about 0.12 inch (Roe and Amman 1970). Therefore, understanding of tree diameter and phloem thickness distributions in lodgepole pine stands of various descriptions would be valuable. Considerable information in the form of stand table data is available for assessing diameter distributions in lodgepole pine stands, but there is virtually none that will allow estimation of phloem thickness in stands of varying descriptions.

A method of modeling phloem thickness distributions for lodgepole pine stands under various management assumptions would be valuable because it could lead to the development of a risk classification for assessing stand vulnerability to the beetle. A starting point is the development of equations for estimating phloem thickness of individual lodgepole pine trees. This paper presents such equations and discusses the functional relationships underlying them.

# METHODS

Data were collected and analyzed under a random sampling design using stratification by habitat types to assess basic site quality differences.

## Observations

The study covered 288 trees in even-aged, unmanaged lodgepole pine stands at elevations ranging from 3,300 to 7,900 feet in western Montana and southeastern Idaho. Measured trees ranged in age from 11 to 155 years; in d.b.h. from 0.8 to 19.5 inches; and, in height from 8 to 103 feet. Data were obtained during remeasurement of permanent plots established for a stand density study and from temporary plots established to widen the range of tree sizes sampled for the phloem study. To minimize experimental error arising from measurement of incomplete phloem growth, the bulk of the sampling was done in the late summer and early fall. The distribution of data and the variation in phloem thickness, in relation to tree diameter, is illustrated in figure 1.

The basic measurements and observational data taken were suggested by literature review and correlation analysis of preliminary data. To provide the necessary growth measurements (in addition to measurements of tree, stand, and site attributes), phloem samples and increment cores were taken from the observation trees as described below.

*Average phloem thickness*.--Thickness to 0.01 inch was determined at breast height from measurement of excised samples, 5/8-inch square. In the permanent plot remeasurements, average phloem thickness was determined from two samples per tree, each located at 180° to the other on the axis of the average d.b.h. of the tree. Variance analysis of the thickness data indicated that error might be reduced by increasing the intensity of sampling for this attribute; therefore, with the supplemental data collected on the temporary plots, two additional phloem samples were excised from each tree. These were located 180° to each other but at right angles to the two measurements indexed on the average d.b.h. of the tree. Analysis of the data revealed no significant difference between the groups.

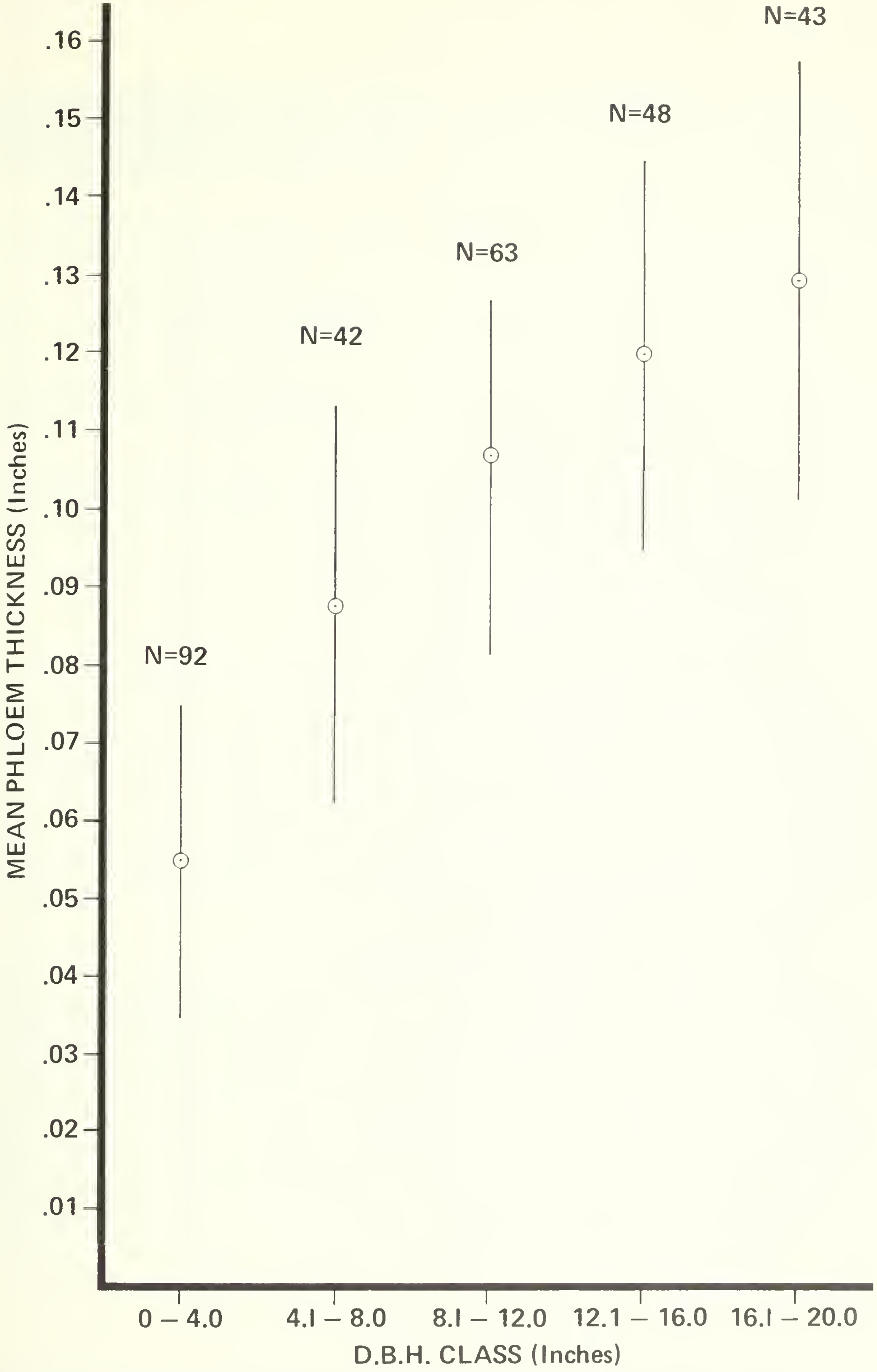

*Figure 1.--Distribution of data, and means and standard deviations of phloem thickness by diameter class.*

*Total "crevice" bark thickness*.--This measurement (after Amman 1969) gives average total bark thickness, disregarding the highly variable ridges and corky tissue of older outer bark, which adds considerable variation to measurements. Measurements to the nearest 0.01 inch were taken from the excised samples used for phloem thickness determination.

*Diameter at breast height, outside bark*.--This was measured to the nearest 0.1 inch with a steel diameter tape.

*Total tree height and crown length*.--Both were measured at taped distances with a clinometer and recorded to the nearest foot.

*Tree age at breast height; average 5- and 10-year radial growth*.--Age and growth measurements to 0.01 inch were obtained from increment cores taken in coincident orientation with the phloem samples from each tree.

*Tree-centered stand density*.--This was determined as the average of two BAF 5 prism counts, each centered 15 feet from the center of the subject tree, in opposite directions and on the axis of the average diameter of the tree. The d.b.h. of each tree tallied was also recorded.

*Elevation*.--Elevation above mean sea level was determined to the nearest 50 feet, from topographical maps or by altimeter.

*Crown class*.--This was classified as dominant, codominant, intermediate, or suppressed, according to standard definitions (Society of American Foresters 1958).

*Habitat types*.--Types were identified according to the classification of Daubenmire and Daubenmire (1968). The habitat types in this study were only tentatively identified, because they are outside the geographical area covered by the original classification. Nevertheless, broad agreement with the specified habitat types should at least establish whether or not phloem thickness variation is related to habitat types.

From the above measurements and observations, a set of independent variables was developed for use in regression analysis.

# Analysis

From the observations taken, 19 individual tree, stand, or site attributes were determined to be independent variables for the gross analysis: habitat type, elevation, crown class, site index, crevice bark thickness, d.b.h., tree height, crown ratio, crown length, age, radial growth, average stand diameter, stand basal area, number of trees per acre, basal area percentile of subject tree,[1] crown competition factor (CCF) (Krajicek and others 1961; Alexander and others 1967), average sum of diameters of prism tally, average sum of diameters squared of prism tally, and average prism count.

The five habitat types considered in the analysis were found to be significantly related to phloem thickness at the 1 percent level of probability. Tests between the individual habitat types, however, according to Students' $t$ distribution, indicated that for these data the habitat types should be statistically considered as two groups. A dummy variable was therefore used, with $X_0 = 1$ for all observations, and the variable $X_1$ being used for habitat-type group identification as follows:

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[1] This is the proportion of basal area represented by all trees in diameter classes up to and including the diameter class of the subject tree-expressed as a percentage of the total stand basal area.

| $X_0$ | $X_1$ | *Habitat type* | |
|---|---|---|---|
| 1 | 1 | = *Pseudotsuga menziesii/Physocarpus malvaceus* | Group 1 |
| 1 | 1 | = *Pseudotsuga menziesii/Symphoricarpos alba* | |
| 1 | 0 | = *Abies lasiocarpa/Pachistima myrsinites* | Group 2 |
| 1 | 0 | = *Abies lasiocarpa/Vaccinium scoparium* | |
| 1 | 0 | = *Pseudotsuga menziesii/Calamagrostis rubescens* | |

The various other independent variables were designated $X_2$ through $X_n$.

Expressions of the form $Y = b_0X_0 + b_1X_1 + b_2X_2 + \dots b_nX_n$ were fitted to the data using the REX computer program of Grosenbaugh (1967) in which:

$Y$ = phloem thickness in inches, or transforms thereof

$X_i$ = the individual independent variables, including various interaction terms

$i = 0$ to $n$.

Fitted regressions were subjected to a full combinatorial screening analysis, in which all combinations of independent variables were compared for their performance in accounting for variation in phloem thickness. Selected residual plottings were made to assay for data trends.

Initial screenings quickly reduced the number of variables showing promise in prediction of phloem thickness. Of the 19 independent variables, only the following were retained for further investigation: (1) habitat-type group, (2) elevation, (3) d.b.h., (4) tree height, (5) crown ratio, (6) crown length, (7) age, (8) radial growth, and (9) average prism count.

Interaction and power terms of the nine retained independent variables were tested, but none added to or furnished improvement over their basic variable form. Selected residual plottings were made to assay for nonhomogeneous variance and to point out any inadequacy of the model. A small amount of nonhomogeneous variance was indicated when phloem thickness (the dependent variable Y) was expressed in inches. A logarithmic transformation of Y was found to compensate, and as its Index of Fit (Furnival 1961) was virtually the same (0.024 vs. 0.022 for Y untransformed), the logarithmic transformation became the preferred form. Plotting of residuals over the individual independent variables did, however, suggest that lateral growth in square inches (basal area increment), as well as radial growth in inches should be included in the analysis, and that the logarithmic transformations of d.b.h., height, crown length, and basal area increment should be used.

From these analyses, a number of equations that are satisfactory for the prediction of phloem thickness under different stand conditions were developed.

# RESULTS AND DISCUSSION

Phloem thickness of lodgepole pine trees can be described by a number of interrelated variables, some of which are more readily measured than others. As an example, in this analysis (as expected) crevice bark thickness was found to be highly correlated with phloem thickness (the coefficient of determination, $r^2 = 0.67$). It was not seriously considered, however, as a useful variable in equations intended for modeling stand phloem distributions, because efforts to measure it can better be spent in measuring phloem thickness directly. The other variables eliminated were all dropped because they failed to contribute sufficiently to the explanation of phloem variation. Some of these might also have been dropped on the basis of practicality, however.

## Relation of Phloem Thickness to the Regression Variables

In the multiple regression analysis, a maximum of 73.5 percent of the variance in observed phloem thickness was accounted for by the following six basic variables: habitat-type group, HT; 5-year basal area increment (BAI), G; d.b.h., d; tree height, h; elevation, El; and age at breast height, A, as shown in regression 1, table 1. Of these, the logarithm of BAI alone (regression 11) accounted for 64 percent of phloem variance. Here, BAI over the most recent 5-year growth period is probably functioning as an indicator of current tree vigor; as such, it can be expected to reflect various tree growth expressions, including phloem thickness.

Habitat-type group was the next most important variable, occurring in all the higher ranking regressions of from two to six independent variables. In the presence of all other final variables, it accounted for an additional 2.8 percent of the total phloem thickness variance--or 9.6 percent of the remaining variance otherwise left unexplained. Nevertheless, because the present identification of types for the study area is uncertain, habitat type was not considered strongly as a usable variable for developing phloem prediction equations.

The relative contribution of the other variables is shown by the differences in percentages of variance accounted for with successive elimination of variables (table 1). Thus, the elimination of age is seen to reduce the percentage only 0.5 point (regression 2); subsequent elimination of elevation, 0.7 point (regression 3); tree height, 1.9 points (regression 4); and d.b.h., 2.1 points (regression 9). The contribution of the other five variables is small when compared to the performance of BAI, but each is statistically significant at the 1 percent level of probability.

Of the six final independent variables, only habitat type and elevation are not individual tree attributes. All, however, are recognized as being either influences on tree vigor (habitat type, elevation, and age) or indirect indicators of vigor (BAI, d.b.h., and height). Because annual xylem and phloem growth are the complementary sum of annual lateral cambial growth, it is not surprising that 5-year basal area increment

Table 1.--*Multiple regression*[1] *relationships of phloem thickness in lodgepole pine trees*

| Regression No. | Basic variables | Percentage of variance accounted for |
|---|---|---|
| 1 | HT,G,d,h,El,A | 73.5 |
| 2 | HT,G,d,h,El | 73.0 |
| 3 | HT,G,d,h | 72.3 |
| 4 | HT,G,d | 70.4 |
| 5 | HT,d,El,h,A | 72.1 |
| 6 | HT,d,El,A | 70.8 |
| 7 | HT,d,El | 61.7 |
| 8 | HT,G,El | 69.3 |
| 9 | HT,G | 68.3 |
| 10 | G,El | 67.1 |
| 11 | G | 64.0 |

[1] For regression 1, the complete multivariable relationship, the equation is:

$$Y = b_0 + b_1HT + b_2\ln G + b_3\ln d + b_4h + b_5El + b_6A,$$

where Y is the natural logarithm (ln) of phloem thickness at breast height in inches; HT = habitat-type group; G = last 5 years of basal area increment in square inches (BAI); d = d.b.h., outside bark, in inches; h = total tree height in feet; El = elevation above sea level in hundreds of feet; and A = tree age at breast height in years. The other regressions use the same forms of the variables, differing only in the combinations of the variables as indicated.

(the most *contemporary* of the growth expressions considered as independent variables) is so strongly related to phloem thickness. The variables, tree height and d.b.h., are similarly regarded as *cumulative* expressions of relative tree vigor.

When used with d.b.h. and height, tree age--aside from its own implications as a vigor factor--seems to serve as an indirect indicator of average growth rate that is nearly as effective in explaining phloem thickness variance as BAI. This can be seen in comparisons of regressions 1, 5, 6, and 7 of table 1. Regression 5 shows that elimination of BAI from the variables of regression 1 results in a decrease in explained variance of only 1.4 percent, whereas elimination of height further reduces the value 1.3 points (regression 5 vs. regression 6). Elimination of age from regression 6, however, results in a drop of 9.1 points--to 61.7 percent (regression 7).

The contribution of elevation, though statistically significant at the 1 percent level, is relatively small. It seems to have greater effect when habitat type is not included in the regression. Compare the difference in explained variance of regressions 8 and 9, containing HT, with that of regressions 10 and 11, not containing HT. It appears that habitat types indirectly account for much of the elevation effect on phloem thickness variation--a not unexpected finding, since elevation is often an element in the delineation of habitat types.

The relationship of elevation to phloem thickness was also influenced by an inadvertently forced positive correlation ($r^2 = 0.20$) between elevation and d.b.h. in the temporary plot data. The requirement that annual phloem growth be essentially finished before sampling could begin limited our ability to find strictly comparable diameter distributions for each of the different habitat types. As a result, habitat types sampled at higher elevations tended, by chance, to have older, larger diameter trees. The elevation-phloem thickness relationship was thus inflated from an $r^2$ value of 0.03 in the permanent plot data to a value of 0.09 in the combined data of this report. The elevation relationships reported here, then, can only be viewed as general indicators of the probable nature of multiple correlations involving elevation.

Neither site index nor the various measures of stand density and local competition used in this study were found to contribute much to phloem thickness estimation. Previous experience (Arthur L. Roe 1970, personal communication) has suggested that habitat types are more likely than site index to indicate basic site quality for a number of lodgepole pine growth expressions. In addition, effects of site quality on phloem thickness are probably represented indirectly by such growth expressions as basal area increment, d.b.h., and height. The relatively limited usefulness of stand density and relative competition measures as indicators was not expected, however. These effects also appear to have been effectively represented by the growth rate expressions included in the model.

Phloem thickness prediction coefficients for habitat-type groupings are not used in the equations because the limited sampling of this study, together with the uncertainties of the habitat-type identification, does not warrant quantification of the relationship. Extension of the habitat-type classification (in progress), followed by intensive sampling of stand conditions, can be expected to make prediction from habitat type reliable. Meanwhile, estimations of the distribution of average phloem thickness within stands of various descriptions can be obtained with the prediction equations for individual trees presented in the next section.

# Estimating Phloem Thickness

A selected number of the relationships of table 1 (minus habitat-type groupings and elevation) were fitted to the data to generate coefficients that would provide prediction equations usable under a variety of stand conditions. These are listed in table 2.

When all data are available, either equation 1 or 2 would probably be preferred for estimation of phloem thickness of individual trees, particularly in computer simulation applications based on stand growth prognosis by the individual tree approach. When basal area increment is not available, however, or when application to stand tables or stand table projections is indicated, other equations may become more practical. The standard errors of estimates are presented in terms of percentages of the mean to allow direct comparison of the equations in original units of phloem measurement (inches).

Uses of the equations should be restricted to the ranges of the independent variables specified under "Observations" on page 2. Extrapolation should be made with caution. The equations should be regarded only as interim estimators for lodgepole pine outside the area of western Montana and southeastern Idaho.

# Conclusions

From the results of this study, we can conclude that:

1. Phloem thickness of lodgepole pine trees is significantly influenced by habitat type. Although significant differences were detectable for only two broad habitat-type groups, more intensive sampling within habitat types might well yield separate estimating equations for many of the types.

2. Phloem thickness of lodgepole pines is functionally related to tree vigor, as shown by the high degrees of positive correlation between phloem thickness and the several growth expressions considered.

Consequently, cultural treatments that result in accelerated growth of the residual stand can be expected also to result in increased phloem thickness for any given age or diameter class. The effect cannot be precisely quantified for sensitive management use until more intensive sampling of habitat types and stand conditions has been done.

Table 2.--*Equations for estimating phloem thickness, Y,*[1] *of lodgepole pine trees*

| Equation No. | Basic variables[2] | Equations | Percentage of variance accounted for | Standard error of estimate (% of mean) |
|---|---|---|---|---|
| 1 | G,d,h,A | $Y = -3.14839 + 0.14278 \ln(G) + 0.47283 \ln(d) - 0.00858 h + 0.00113 A$ | 69.4 | 27.6 |
| 2 | G,d,h | $Y = -3.17152 + 0.12591 \ln(G) + 0.50932 \ln(d) - 0.0077 h$ | 69.3 | 27.7 |
| 3 | d,h,A | $Y = -3.40418 + 0.85547 \ln(d) - 0.01151 h - 0.00105 A$ | 67.1 | 28.8 |
| 4 | d,h | $Y = -3.41275 + 0.866 \ln(d) - 0.013 h$ | 66.9 | 28.8 |
| 5 | d,A | $Y = -3.3843 + 0.63143 \ln(d) - 0.00432 A$ | 63.2 | 30.6 |

[1] Y = natural logarithm of phloem thickness at breast height, in inches.

[2] G = last 5 years of basal area increment in square inches; d = d.b.h., outside bark, in inches; h = total tree height in feet; A = tree age at breast height in years.

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OXFORD: 523.1. KEYWORDS: bark thickness, phloem thickness, lodgepole pine, mountain pine beetle.

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Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)
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